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Novel manufacturing route for scale up production of Terahertz technology devices

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Abstract

The advances in terahertz technology drive the needs for the design and manufacture of waveguide devices that integrate complex 3D miniaturised components with meso and micro scale functional features and structures. Therefore, in parallel with the development of such terahertz devices it is necessary to design and validate new manufacturing platforms for their batch production. Especially, with the frequency increase the dimensions of the waveguide functional structures decrease and they are in the micro range from 200 μm to 50 μm with tight requirements for accuracy and surface integrity as they determine the devices' performance. In this context, this paper presents a novel manufacturing route for scale up production of terahertz components, which integrates CNC milling and laser micro-machining. A solution to overcome the resulting tapering of the laser ablated volumes while achieving a high accuracy and surface integrity of the machined structures is proposed in this research. In addition, an approach for two-side processing of waveguide structures within one laser machining setup is described that employs a higher precision alignment procedure. The capabilities of the proposed manufacturing route are demonstrated on a terahertz waveguide component that is functionally tested to assess the effects of the achieved dimensional accuracy and surface integrity on its performance. The results show that the proposed manufacturing solution can be a very promising alternative for the scale up production of terahertz components.

Keywords: terahertz devices, process integration, complex two-side laser processing

1. Introduction

Terahertz technology has attracted significant research interest in the past decade because it enables the development of innovative sensing systems for diverse application areas such as multiresidue analysis of agrichemicals, medical diagnostics, process monitoring systems for industrial products, wireless communications, and biometric security [1]. Due to the 2.5D geometrical design and micro-scale functional structures of terahertz devices, their fabrication methods are exclusively based on photoresist micromanufacturing techniques. They are capable of producing high aspect ratio structures across different size scales [2]. However, the photoresist micro-fabrication methods include multi-step processing and require clean technologies that make the manufacturing platform for terahertz components distinctly different from those used for low frequencies, e.g. CNC machining of copper workpieces. In addition, these methods have intrinsic limitations regarding the materials that can be processed and thus used in designing terahertz devices; also, they introduce constraints regarding the devices' design, especially the necessity to split the designs into structured Si or SU8 layers that have to be metalized afterwards before integrating them with high precision into the 2.5D devices' geometry [3]. These limitations make the photoresist-based production approach for terahertz devices capital intensive and thus potentially viable only for relatively big batch sizes while the unit costs are still relatively high due to the use of clean room

manufacturing technologies and the required alignment and packaging operations.

At the same time, laser micro machining (LMM) is a very attractive solution for the fabrication of wide range of products and has some very appealing advantages over other micro machining processes (MMPs) [4]. Especially, some critical advantages of LMM include non-contact machining, ability to process wide range of materials and complex free-form (3D) surfaces that incorporate functional features with wide range of sizes, and capabilities for in-situ selective surface characteristics customization [5]. Thus, LMM offers manufacturing capabilities that make it a very interesting alternative for the fabrication of terahertz technology devices, in particular the flexibility of a direct write process for producing 3D structures onto metal substrates with good electrical conductivity, e.g. copper, and thus to eliminate the necessity of expensive follow up coating and assembly operations. This can lead to significant reductions in production times and cost while also increasing the accuracy of the terahertz devices due to the fact that important functional features are produced in a single machining operation. However, an important shortcoming of LMM is that this technology is only viable when small volumes of material have to be removed due to its relatively low removal rates in comparison to milling [4]. Furthermore, the laser processed volumes also have a taper angle [5], which can have a significant negative effect on the terahertz devices' performance due to their very high sensitivity to any variations of their dimensional accuracy and surface integrity. Thus, these LLM limitations have to be addressed in order to

consider this technology as a potential alternative to the photoresist micromanufacturing techniques and thus to benefit from its appealing direct write capabilities in the fabrication of terahertz products.

In this context, it is very important to design and implement new solutions for overcoming the LMM limitations. In particular, possible integration of this technology with other complimentary processes into a hybrid manufacturing platform should be considered in order to use the capabilities of one technology for overcoming shortcomings of another [6]. For example, a combination of micro-milling and laser structuring was reported to produce complex biotechnology products with feature sizes smaller than the cutting tool diameter without compromising machining time. This manufacturing platform benefits from the complementary capabilities of its constituent technologies for a higher removal rates and higher machining resolution, respectively [7]. However, an important limitation of current hybrid manufacturing platforms is that they are product specific, which makes their fabrication capabilities highly dependent on products' specific technical requirements and also vulnerable to design changes even within their respective application areas [6]. Thus, the process integration techniques in hybrid manufacturing platforms should offer sufficient flexibility to ensure that they can be adapted easily to different product designs with their specific technical requirements.

The aim of the research reported in this paper is to develop a novel manufacturing route, which can deliver a scale-up production of diverse range of terahertz waveguide devices with the required level of dimensional accuracy and surface integrity. This is achieved by combining the capabilities of the LMM and milling technologies and thus to benefit from the higher removal rates of the later for machining relatively large features of the terahertz devices, while laser machining is employed to produce the devices' functional micro features. The next section describes the proposed process chain together with the developed process integration solutions for a higher flexibility. Then, a simple terahertz waveguide device was manufactured to demonstrate the capabilities of the proposed hybrid manufacturing platform. The performance of the device was analysed to understand better the effects of the achieved accuracy and surface integrity on the waveguide functionality.

2. Process chain development

The employed process chain for the scale up production of terahertz devices is exemplified in Figure 1. The developed software and hardware solutions in order to achieve the necessary level of flexibility in integrating laser micro-machining and micro-milling includes: (i) a modular workholding device for positioning workpieces on multiple setups with repeatability better than 1 μm ; (ii) an automated workpieces' setting up routine to reduce the operators' efforts and the necessary time for setting up workpieces on the LMM systems while increasing the alignment accuracy and precision. A detailed description of these two solutions is provided in another paper [8].

The fabrication chain starts with the mounting of a copper bar into a CNC turning system where the machining of meso-scale features of the terahertz device, e.g. alignment and fixing holes, was carried out

together with parting-off of the workpiece to the desired thickness for further LMM operations. Furthermore, an alignment mark (a cross) is also machined in order to facilitate the precise alignment of the terahertz component for follow up processing in the LMM system. The cut-off workpiece is fixed onto the interface plate of a common pallet, which is then placed in the LMM module, where the functional features of the terahertz device are produced. In the next step of the proposed manufacturing route, the laser ablated functional features are scanned with a 3D optical measurement system to acquire data about any deviations from the CAD model, e.g. the tapering angle on the features. Then, this data is used for further machining of rest volumes (the difference between the actual shape and the CAD model) by LMM and thus to achieve the required geometrical accuracy of the functional features. Such further laser processing for minimising any deviations from the CAD model, e.g. to produce side walls with tapering angle less than $\pm 1^\circ$, requires either rotation of the workpiece employing rotary stages or tilting of the laser beam. Thus, this final LMM step necessitates an additional synchronization of optical (the scan head) and mechanical axes' movements to achieve the required level of machining accuracy, repeatability and reproducibility (ARR). In particular, any use of the rotary stage in the LMM setup leads to misalignments in both the lateral position (in XY plane) and vertical position (along Z axis) of the targeted laser-material interaction points (along the 3D beam path). Thus, to compensate the effects of such misalignments on the machining results, a software routine was developed for calculating the necessary offsets of the laser beam on the workpiece. Then, these offset values are used to apply corrective movements with the linear mechanical stages. Due to the size restriction for this paper the detailed description of the developed software tool to automate the execution of such compensation routine is not included. The final step of the process chain includes removing and fixing again the workpiece on the pallet for laser processing of its second side and thus to complete the machining of the terahertz component. The alignment of the two machined sides of the workpiece in the LMM module is carried out with the automated workpiece setting up routine.

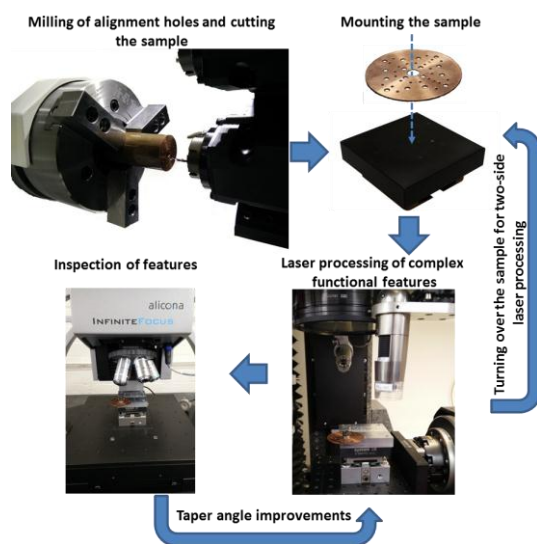


Fig. 1. Process chain of the proposed manufacturing route.

3. Experimental set-up

3.1. Material

The material used in the experiment is a special grade of copper bars ($\text{Cu}_{99.55}\text{S}_{0.45}$) with a diameter of 50 mm that are commonly used for producing EDM electrodes. This material was selected due to its improved machinability and thus to achieve the required surface finish during the milling, drilling or turning operations in the first step of the proposed process chain.

3.2. Machining set-up

The CNC precision turning machine that was used in this research was Mazak Quick Turn Smart 200M with a driven tool turret. The maximum rotational speed of the main spindle is up to 5000 RPM, while the maximum rotational speed of the driven head is 6000 RPM.

The LMM system, which has been used in the experiment, incorporates 5 mechanical axes (3 linear axes with maximum travel of up to 300 mm and 2 rotary axes) and 3 optical axes. It integrates an Yb-doped sub-pico 5W laser sources from Amplitude Systemes that operates at a central wavelength of 1030nm and maximum repetitions rates of 500 KHz. The laser system also has a 100mm telecentric focusing lens with a machining field of view of 35 mm by 35mm.

The inspection of the produced terahertz waveguide devices was performed on an optical Focus Variation microscope, namely Alicona InfiniteFocus G4. With this system measurements of both form and surface topography were carried out with maximum lateral and vertical resolutions of 400 nm and 10 nm, respectively.

3.3. Experimental validation

The experimental validation of the proposed process chain was performed on a simple terahertz waveguide device, namely a WR-3 2nd order filter as, shown in Fig. 2. It includes two symmetrical waveguide structures on a plate with dimensions 19.05 mm x 19.05 mm and a rectangular through hole between the two sides. The used laser machining parameters are provided in Table 1.

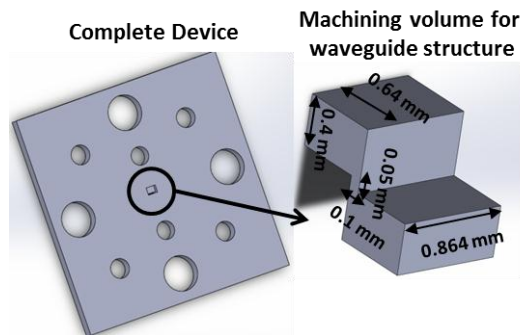


Fig. 2. The design of the microwave filter together with its important nominal dimensions.

4. Results and Discussions

Figures 3 and 4 show the results from the performed measurements of the waveguide structure before and after the second LMM operation to minimise tapering angle of its side walls, respectively. Figure 5

Table 1

Laser parameters for the experimental validation test

Laser parameter	Units	Values
Power	W	4.2
Frequency	kHz	250
Scanning Speed	m/s	1
Pulse duration	fs	310
Beam diameter	μm	30
Hatch style	-	Random
Hatch Pitch	μm	4
Layers (single structure)	-	286
Layers (through hole)	-	36

also shows measurements of the waveguide structure, which was produced on the other side of the workpiece after repositioning it on the pallet. It can be seen in Figure 3 that the dimensional accuracy achieved is better than 10 μm , while the structure depth deviation from the nominal value is within $\pm 5 \mu\text{m}$. Furthermore, Figure 3 shows that the taper angle after the first LMM operation is $\sim 12^\circ$, which can lead to significant deterioration of the waveguide performance. The laser machining time was 270 s, which represent a material removal rate of 0.05 mm^3/s .

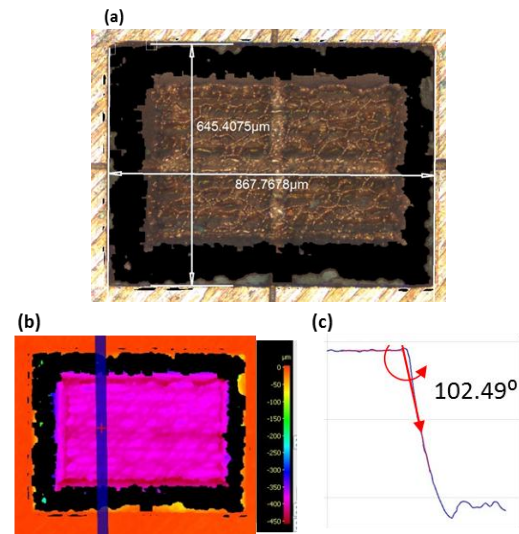


Fig. 3. Laser machining results of the structure first side: (a) lateral dimension, (b) pseudo-colour map of depth and (c) taper angle.

It can be seen in Figure 4, that the tapering angle was reduced down to less than 1° after employing the specially developed CNC routine for multi-axes LMM that includes positioning of the workpiece utilising both linear and rotary stages and then perform laser processing using the optical axes. The G-code of this routine did not include laser beam diameter compensations and therefore the length and width of the structure increased symmetrically with 20 μm as it is depicted in Figure 4. The figure also shows the adjacent rectangular through hole to the vertical walls of the waveguide structure that was successfully machined, too. The hole machining time was 20s while the time required to execute the taper angle improvements LMM routine was 50 s, which increased the overall machining time by 18.5%. It should be noted that the focus of the feasibility study was to demonstrate the capabilities of LMM for producing terahertz waveguide structures with required accuracy and surface integrity. Thus, the laser settings were not

optimized to utilize fully the capabilities of the laser system. Thus, it can be expected that the material removal rates can be improved by at least a factor of 2 by employing the maximum repetition frequency (500 kHz) available on the used laser source and also by increasing the scanning speed to 2 m/s. Comparing the machining results of the two symmetrical waveguide structures on the two sides of the workpiece, it can be concluded that the reproducibility of the machining results is better than 2 μm . Furthermore, the deviation of the respective widths of the rectangular through hole on the two sides of the sample (see Fig.4 and Fig. 5) demonstrates that an alignment accuracy of better than 2 μm was achieved by utilizing the automated workpiece setting up routine.

Finally, Figure 6 shows the results from the performed functional tests of the produced terahertz waveguide filter. It can be clearly seen that the measured S-parameters follow the simulated S-parameters for this terahertz device. There is some frequency shift of the S-parameters because no beam diameter compensation was performed for the second LMM operation. This also exemplifies the sensitivity of the waveguide structures to any deviations from its nominal dimensions.

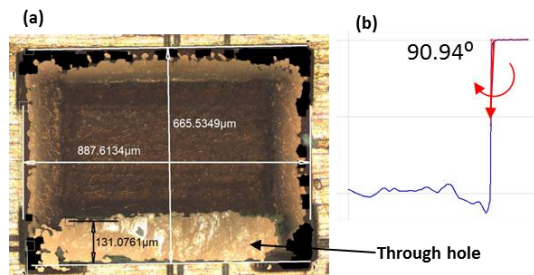


Fig.4. Laser machining results of the first side of the workpiece after the taper angle improvements: (a) lateral dimensions, (b) pseudo-colour map of depth and (c) taper angle.

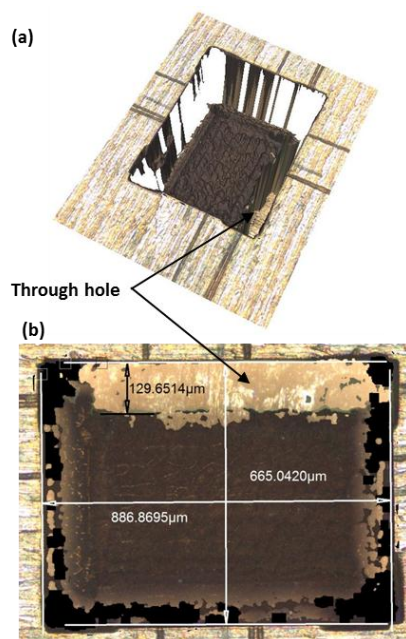


Fig.5. Lateral dimensions of the waveguide structure on the second side of the workpiece after carrying out taper angle improvements: (a) 3D view and (b) top view.

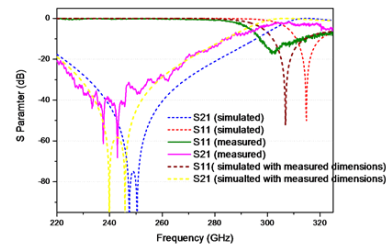


Fig. 6 Performance analysis of the terahertz waveguide filter

5. Conclusions

This paper presents a novel manufacturing route for the scale up production of terahertz technology components. The following conclusions could be drawn from this research:

- Significant reduction of production time for terahertz components could be achieved by employing milling for the fabrication of the meso scale structures while laser micro-machining is utilized for the fabrication of the micro-scale functional features.
- Two-side LMM of complex terahertz waveguide devices is feasible by employing specialized workpiece setting up routine.
- Significant taper angle improvements of the laser machined volumes can be achieved by implementing specialized CNC multi-axes routines.

Acknowledgements

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